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Laser Assisted Soldering: Microdroplet Accumulation With a Microjet Device

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Background and Objective: **We investigated the feasibility of a microjet to dispense protein solder for laser assisted soldering.**
Study Design: **Successive micro solder droplets were deposited on rat dermis and bovine intima specimens. Fixed laser exposure was synchronized with the jetting of each droplet. After photocoagulation, each specimen was cut into two halves at the center of solder coagulum. One half was fixed immediately, while the other half was soaked in phosphate-buffered saline for a designated hydration period before fixation (1 hour, 1, 2, and 7 days). After each hydration period, all tissue specimens were prepared for scanning electron microscopy (SEM).**
Results: **Stable solder coagulum was created by successive photocoagulation of microdroplets even after the soldered tissue exposed to 1 week of hydration.**
Conclusions: **This preliminary study suggested that tissue soldering with successive microdroplets is feasible even with fixed laser parameters without active feedback control. Lasers Surg. Med. 23:213–220, 1998.**

Key words: endoscopic surgery; laparoscopic surgery; laser-tissue interaction; tissue soldering

INTRODUCTION

One major drawback of laser tissue soldering is the lack of a reliable method to assure proper solder coagulation at the tissue. In most cases, visual feedback is used to determine the status of the coagulation process [1–4]. The term "occurrence of desiccation" is often used in the literature to describe the visual cue used for deciding the coagulation extent. "Occurrence of desiccation" is the point where the solder starts appearing pale/diffuse and perhaps there is slight solder/tissue discoloration during the coagulation process. Surface temperature is another feedback parameter that has been investigated [5–7]. Since photocoagulation is a rate process, which means it depends on both the heating time and temperature [8], infrared radiometry has been used to monitor solder coagulation by advancing the laser beam when the solder surface reaches a certain temperature [9–11]. However, the most crucial region of the whole process, the solder-tissue interface, is buried at the bottom of the solder. Therefore, sur-

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face information may provide a reliable estimate of coagulation extent at the solder-tissue interface only when the solder thickness is consistent and the optical and thermal properties of the solder and the tissue remain constant. In a previous study, we have demonstrated that under-coagulated solder may result in premature solder detachment due to poor solder-tissue fusion [12]. This detachment phenomenon is more susceptible when the tissue substrate has a smooth surface and the welded tissue is exposed in a prolonged period to a hydrated environment.

Under-coagulation can be avoided when the solder thickness is small compared to solder absorption depth. Recently, we reported a study using accumulative micro solder droplets to perform tissue repair [13]. Acute failure strength of the solder was 257 N/cm^2, significantly higher than the failure strength of the tissue substrate native aorta (76 N/cm^2). However, solder droplet was deposited manually with a precision micro-syringe and then laser irradiated one droplet at a time. This technique worked well in our in vitro model, but the whole process was very time consuming. This small droplet soldering technique could be made feasible in a clinical setting by automating solder deposition with a microjet device. The microjet technology has been used in non-welding projects to deposit small amounts of biological fluids [14–16]. The microjet can precisely control droplet volume as small as tens of a nanoliter [17]. The microjet technology may provide a viable fluid dispensing technique for laser soldering.

In this study, the feasibility of dispensing in albumin-based solder with a microjet was investigated. The stability of solder-tissue fusion was evaluated by exposing the soldered specimens to a hydrated environment.

MATERIAL AND METHODS

Solder Composition

The protein solder was made based on the recipe from Pohl and Bass [18]. It was composed of 25% human serum albumin and 0.5% sodium hyaluronate dissolved in deionized water. An absorbing dye, Indocyanine Green (ICG), with a concentration of 2.5 mg/mL was added to enhance solder light absorption from a diode laser at 808 nm. Similar solder formulation has been used in other studies [1,9,19].

Successive Small Droplet Deposition

The setup of the microdroplet experiment is shown in Figure 1. The microjet nozzle was aimed perpendicularly at the tissue substrate. The optical fiber was oriented at about 30° from the microjet and aligned with the nozzle target region. A 60 μm diameter orifice was used in conjunction with a solenoid driven microjet (MicroFab Technologies, Inc., Plano, TX). The microjet controller regulated the delay and timing of the microjet and the laser. The microjet settings used in this study were driving voltage of 35 V, pulse duration of 6.4 ms, back-pressure of 70 PSI, and repetition rate of 1 Hz. The microjet was not able to dispense the viscous solder. Therefore, a 1:8 dilution with deionized water was used. ICG was added after dilution of the solder. The microdroplet volume was 0.2–0.3 μL/drop with a droplet diameter of about 700 μm. The laser source was a 808 nm diode laser. A pulse generator triggered both the laser and the microjet controller. Laser light was coupled into a 400 μm fiber. Since the optical fiber was aimed at an angle, the laser spot diameter at the target was 2.5–3.5 mm. Each droplet was exposed to a stationary laser beam with a fixed laser exposure of 140 W/cm^2 for half a second. Since the laser beam diameter exceeded the solder droplet diameter, not all of the laser irradiance was absorbed by the solder droplets. Five microdroplets of solder were deposited and coagulated on each tissue specimen. Both rat skin dermis and bovine intima were used for these experiments.

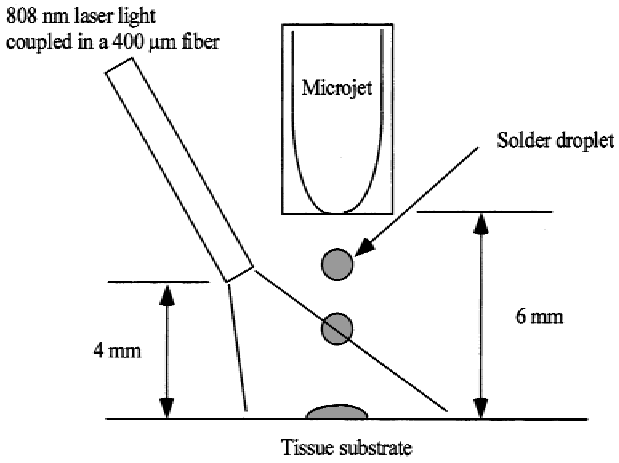

Fig. 1. Setup for microjet laser soldering experiment.

Tissue Fixation and Hydration

Following the experiments, a full thickness incision was cut at the center of the soldered specimen exposing the solder-tissue cross-section. One half was immediately fixed in 1% glutaraldehyde and the other was soaked in phosphate-buffered saline (PBS) for the prescribed observa-

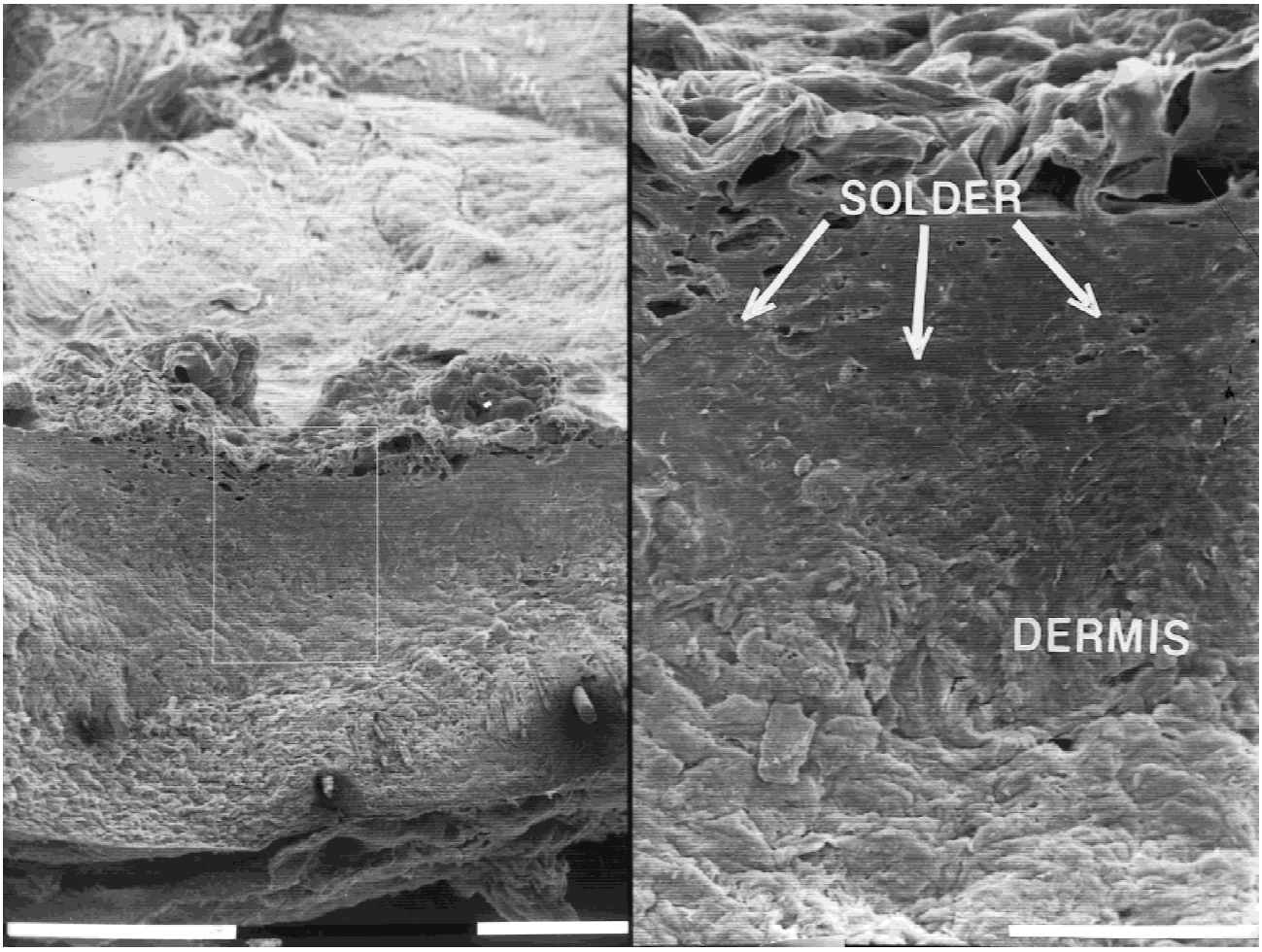

Fig. 2. Successive droplet rat skin specimen, after 1 day of hydration. As shown in the right hand panel, fusion of solder-tissue interface was achieved. Original magnification: left, ×44; right, ×200. Scale bar: left, 500 μm; right, 111 μm.

tion period before fixation. The observation periods were 1 hour, 1, 2, and 7 days. One specimen from each tissue type was used for each hydration period.

SEM Analysis

The tissue preparation for SEM analysis included specimen dehydration in graded ethanols (25, 50, 75, 95, 100, and 100%), critical point drying, and specimen coating with a thin layer of gold-palladium. SEM analysis was performed on a Philips 515 scanning electron microscope.

RESULTS

Successive Small Droplet Skin Specimens

Small protein volume was achieved with the microjet setup as illustrated in Figure 1. We used a microscope to monitor the jetting process. We noted that when the micro solder droplets deposited on a tissue substrate, the solder would remain in its liquid form. Liquid solder left uncoagulated would eventually dehydrate and be stuck on the substrate surface. Once rehydrated, however, the uncoagulated dried protein solder would dissolve in water.

In this study, the thermal coagulum was composed of five solder droplets with thickness of 50–70 μm. The control and hydrated specimens were well attached to the tissue substrate. The left panel of Figure 2 shows an oblique view of the solder-tissue cross section. The solder was well coagulated onto the dermis by the laser radiation between each droplet. There was some vapor vacuoles that likely resulted from the boiling of solder mixture during photocoagulation. At higher magnifications, fusion of solder and dermal substrate was observed (Fig. 2, right panel). Figure 3 shows the difference between native skin collagen fibers (left panel) and the fusion of solder

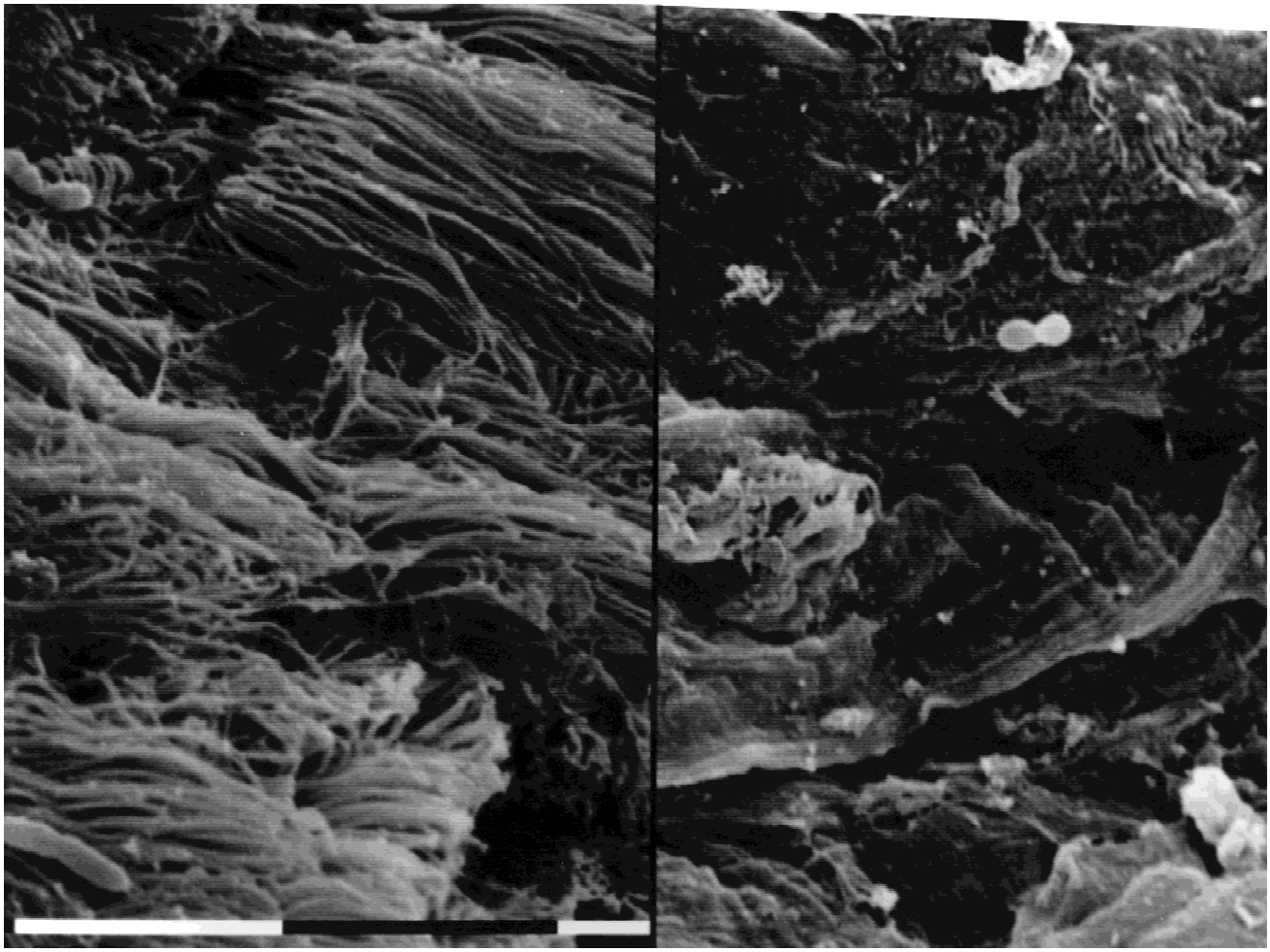

Fig. 3. Successive droplet rat skin specimen, after 1 day of hydration. Original magnification: ×5,000. Left panel is native collagen fibers and right panel is fused solder-collagen matrix. Scale bar: 5 μm.

and collagen fibers (right panel). Using fusion of collagen fibrils as an indication for tissue damage, the extent of underlying coagulation was approximately 250–400 μm. Direct light absorption by aorta tissue at 810 nm is minimal. Therefore, most of the thermal damage was likely a result of thermal diffusion from the heated solder. Figure 4 shows that the solder was still attached to a rat dermis specimen after 7 days of hydration.

Successive Small Droplet Intima Specimens

The overall solder coagulum thickness was about 50–100 μm. All the control and hydrated specimens adhered well to the aortal surface. Steam vacuoles were often noted at the solder (Fig. 5, left panel). Fusion of solder and aortal collagen fibers produced a stable solder-tissue bond (Fig. 5, right panel).

DISCUSSION

In a previous study, we noted that when a high temperature gradient generated across the solder thickness by using conventional soldering technique, even though the solder surface may appear to be coagulated, under-coagulation of solder could occur at the solder-tissue interface. Under-coagulated solder-tissue interface can cause premature solder detachment in a hydrated environment [12]. Soldering with microdroplets minimizes solder temperature gradient that assures a more uniform and thorough solder-tissue coagulation providing a more predictable solder adhesion to the tissue substrate. The microjet allows microdroplets of solder to be deposited at the tissue substrate. Each droplet can be totally coagulated by fixed laser parameters. To establish a sizable coagulum, successive droplets can be de-

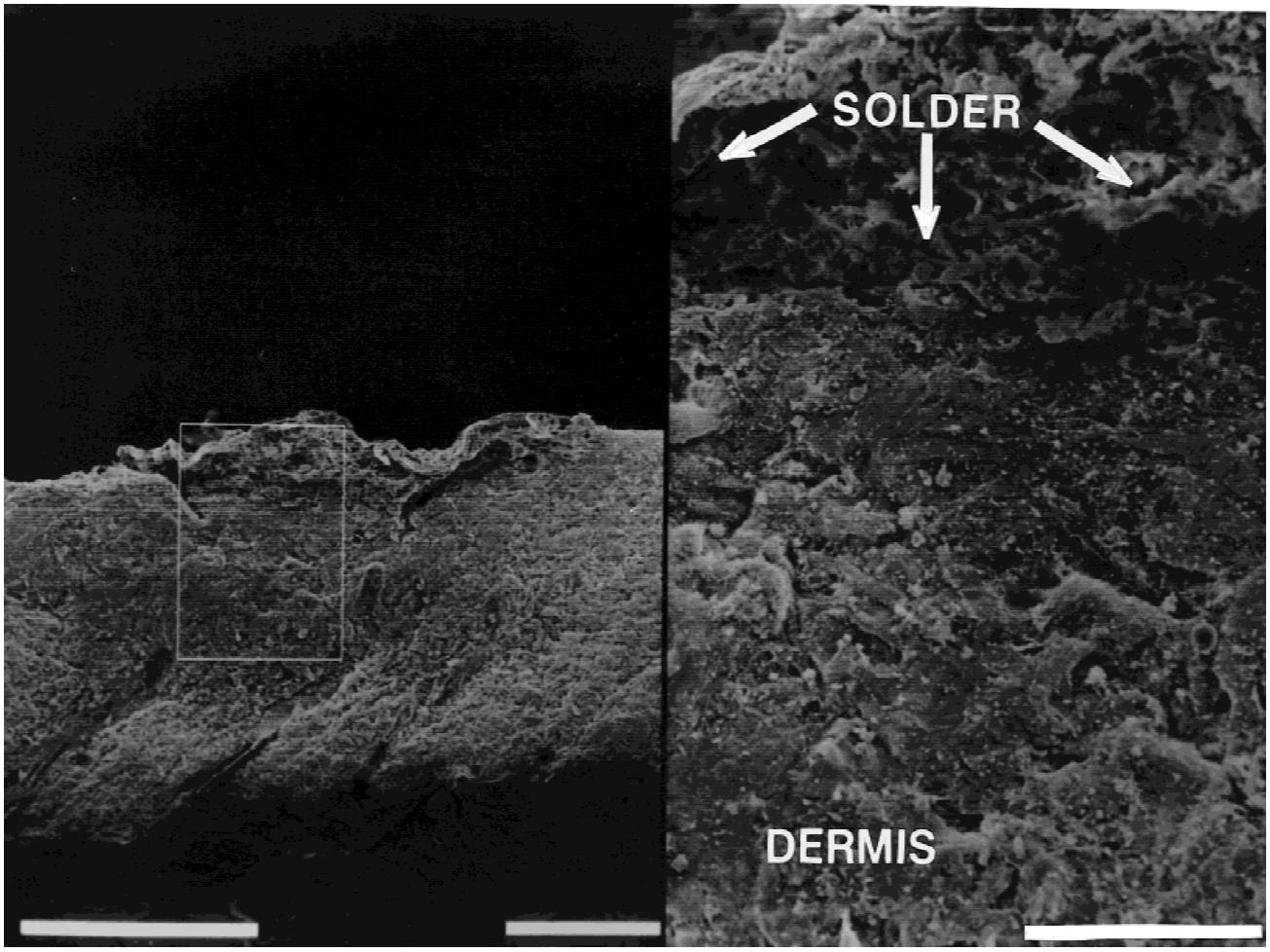

Fig. 4. Successive droplet rat skin specimen after 7 days of hydration. The arrows define the solder-tissue interface. Original magnification: left, ×44; right, ×208. Scale bar: left, 500 μm; right, 125 μm.

posited. Complete coagulation avoids the detachment problem associated with under-coagulated solder at the solder-tissue interface.

For conventional laser soldering, tissue thermal damage depends on how solder is distributed over tissue and the amount of laser energy absorbed by the solder and the surrounding tissue. Light dosimetry control can be quite subjective. Excessive tissue heating may happen during soldering especially when laser energy is not carefully regulated. Poppas et al. [9] conducted a study by using a temperature-controlled laser system to regulate light dosimetry for soldering. However, like most conventional soldering studies, they also used visual feedback for end-point control. In a porcine skin model, they reported coagulation depth ranging from 2–3 mm depending on the controlled temperature. It should be noted that they used a 1.3 μm laser and solder without dye added, so the underlying tissue would also directly absorb the laser irradiation.

The microjet soldering technique utilizes pulses of laser energy to coagulate each micro solder droplet. From a previous study, the optical depth of solder with the same ICG concentration was determined to be 32 μm [20]. In this study, the laser spot size of 3 mm is much larger than the solder optical depth. Therefore, the thermal diffusion time, τ, can be expressed by

$$\tau = \frac{\delta^2}{4\alpha},$$

where δ is the optical depth of solder and α is the thermal diffusivity [21]. Using water thermal diffusivity, $\alpha = 0.15$ mm^2/sec, the thermal diffusion time is approximately 1.7 msec. Since the pulse

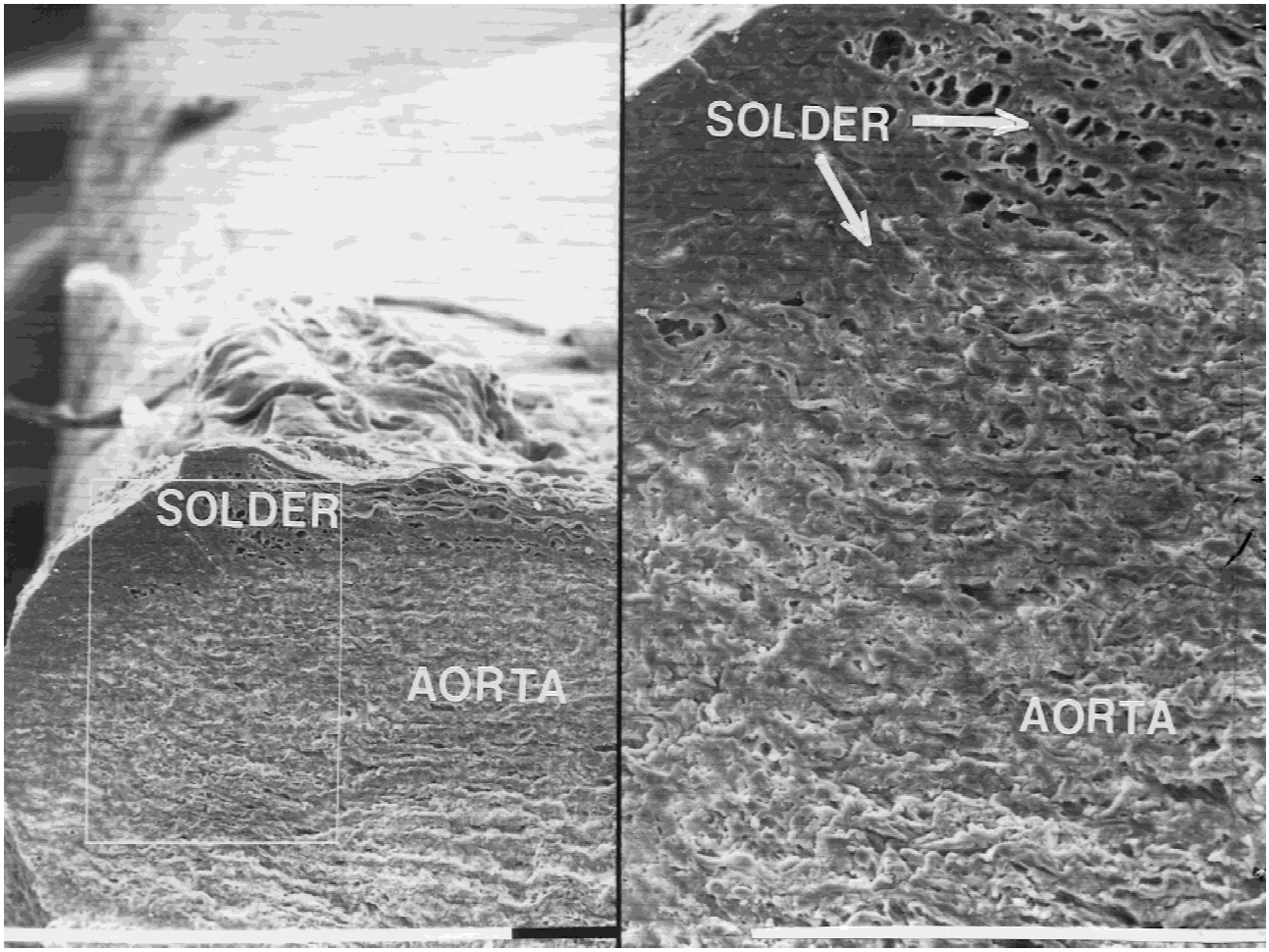

Fig. 5. Successive droplet bovine intima specimen, after 48 hours of hydration. Fusion of solder-tissue interface was noted. Original magnification: left, ×97; right, ×291. Scale Bar: left, 500 μm; right, 167 μm.

length used in this study (0.5 sec) is longer than the diffusion time, the thermal energy penetrates beyond the solder into tissue during each laser pulse. We used a laser irradiance of 140 W/cm^2 to ensure a reliable coagulum established between the solder and tissue substrate within a short exposure time. As multiple solder droplets and laser pulses were delivered, more energy was diffused into the tissue substrate. We noted that the underlying tissue coagulation was approximately 250–400 μm. The depth of damage is a result of heat conducted from the irradiated droplets. Minimal thermal damage to underlying tissue is desirable for dye-enhanced tissue soldering. We believe that the depth of coagulation with this technique can be minimized once the laser and solder parameters are optimized. For example, minimizing irradiation time will reduce depth of damage.

Another factor that may have contributed to solder heating is the dynamic changes of solder optical properties. We noted that as each solder droplet was photocoagulated, the green tint of the ICG solder became darker, suggesting that moisture in the solder evaporated. As a result, local ICG density increased, which made the solder coagulum more efficient in absorbing laser light. Therefore, the temperature at the soldered area progressively increased with successive solder droplet and laser irradiation. Eventually, conduction of heat generated in the solder coagulum caused coagulation of the underlying tissue. This further assured a reliable fusion between the solder coagulum and the underlying tissue, as well as between successive solder droplets.

A solenoid driven microjet was used for these experiments. The smallest droplet volume deposited by this microjet was 0.2 μL. Moreover, when running at frequency beyond 10 Hz, heat generated by the jetting mechanism clogged the orifice

with thermally denatured solder. Friction generated by opening and shutting the valve at a high repetition rate elevates solder temperature to a point that caused coagulation of solder in the microjet. The maximum jetting frequency without clogging was 2 Hz using a dilution ratio of 8:1.

A more promising technology of piezoelectric microjet may alleviate this problem. This technology will allow a higher repetition rate without causing premature solder heating inside the orifice. Unlike a mechanical valve used by the solenoid microjet, this technology will employ a piezo-electric crystal to dispense the fluid. Moreover, the droplet volume can be controlled more precisely since the piezo-electric microjet is capable of jetting droplets in the order of a nanoliter.

It is our vision to develop an automated soldering system that can jet viscous solder. As mentioned earlier, we have performed tissue repairs using the accumulative small droplet technique with a microsyringe to deposit viscous solder [13]. There are also reports that have shown higher albumin density may provide more stable repairs in soldering [22–23]. Such a device may allow consistent microdroplets of viscous solder to be irradiated by laser energy that ensures sufficient solder coagulation. Furthermore, this device may be used without active feedback control of laser exposure. Therefore, tissue repairs can be performed on hard-to-reach lesions where visual and/or other means of feedback are difficult.

This preliminary study has demonstrated that the successive microdroplet method can provide stable solder fusion to tissue substrates. Nevertheless, steam vacuoles in the solder coagulum may still produce suboptimal welds. A densely packed coagulum likely provides a stronger weld than one filled with vacuoles. Optimizing the laser parameters could minimize these vacuoles and reduce underlying tissue damage. Further study in characterizing weld strength using this technique is underway.

CONCLUSIONS

The feasibility of performing laser soldering by successively coagulating micro solder droplets has been investigated. SEM analysis demonstrated that stable solder-tissue adhesion even when the soldered tissue was exposed to a hydrated environment. Underlying tissue damage of 250–400 mm was noted in this study. Optimization of laser and ICG parameters may minimize tissue thermal damage. This technology holds promise to automating tissue soldering without using an active feedback control mechanism to monitor the soldering process.

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